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Review of economic assessment of hybrid photovoltaic-diesel-battery power systems for residential loads for different provinces of Saudi Arabia

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ABSTRACT

Presently, the world is considering renewable solar energy as an indispensable/long-term/nature-friendly option for power generation. The Kingdom of Saudi Arabia (K.S.A) is blessed with considerable amount of solar radiation. Commercial/residential buildings in K.S.A. consume about 10–45% of the total electric energy. In the present paper, the economic analysis of utilization of hybrid PV–diesel-battery power systems to meet the load of a typical residential building (with annual electrical energy demand of 35,120 kWh) in different provinces/zones of K.S.A. has been studied by analyzing long-term solar radiation data. Five geographically distinct sites representing different provinces of the Kingdom have been selected. The monthly average daily solar radiation of K.S.A. varies from 3.03–7.51 kWh/m^2. NREL's (HOMER Energy's) HOMER software has been employed to perform the analysis.

The simulation results indicate that for a hybrid system composed of 4 kWp PV system together with 10 kW diesel system and a battery storage of 3 h of autonomy (equivalent to three hours of average load), the PV penetration is 22%., 21%, 22%, 20%, and 20% at Abha (Southern Province), Hofuf (Eastern Province), Qurayat (Northern Province), Taif (Western Province), and Riyadh (Central Province) respectively. The cost of generating energy (COE, US$/kWh) from the above hybrid system has been found to be 0.179 $/kWh, 0.179 $/kWh, 0.178 $/kWh, 0.180 $/kWh, and 0.181 $/kWh at Abha, Hofuf, Qurayat, Taif, and Riyadh respectively. For a given hybrid system, the PV penetration is higher in Southern and Northern Province as compared to other provinces. Also, the study has examined the impact of PV penetration on: carbon emissions (Tons/year), diesel fuel consumption, Net Present Cost, cost of energy, etc. Furthermore, for a given hybrid configuration (for Northern Province), the study exhibits that increase in PV capacity results in decrease in the diesel-fuel-consumption/carbon-emissions and increase in COE./NPC/excess-energy.

Contents

1. Introduction

The world is highly concerned about depletion/rising-cost of non-renewable energy resources, energy security, its access, and environmental impacts of energy usage. At the same time, with distributed and clean energy (wind and solar) resources becoming

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widespread, there is an increased worldwide attention towards exploitation of renewable sources of energy (to mitigate energy crisis and to subside environmental degradation due to burning of fossil fuels). The Kingdom of Saudi Arabia's (K.S.A.) total installed electricity generation capacity has increased significantly (from 1141 MW in 1975 to 46,000 MW in 2010; also the peak demand is expected to be 59,000 MW in 2020) during the last two decades. The annual demand growth is 8 percent. About 70% of the power generated goes into air-conditioning [1–4]. The above increase can be attributed to rapid growth in residential, commercial, and industrial sectors. Literature reveals that commercial/residential buildings in Saudi Arabia consume 10–45% of the total electric energy consumption [1]. Increased rate of electric energy consumption constitutes one of the biggest problems being encountered by the electric companies in the K.S.A. In order to cope with the increasing electricity consumption trends, it is desirable to explore every possible avenue for generating more energy [4]. One of the options to overcome this energy issue is by utilization of solar energy [5]. Since K.S.A. is blessed with high solar radiation levels, an appreciable portion of its energy needs may be harnessed from solar energy. Solar radiation intensities of geographically different provinces of the Kingdom are presented in Table 1. More importantly, the future prospects of renewable/solar photovoltaic (PV) based power systems are expected to be promising.

Solar energy is one of the in-exhaustible/sustainable, site-dependent, clean (does not produce emissions that contribute to greenhouse effect) source of renewable energy options that is being pursued by a number of countries with monthly average daily solar radiation level in the range of 3–6 kWh/m^2, in an effort to reduce their dependence on fossil-based non-renewable fuels [6–13]. Solar collectors can be classified as either solar thermal energy converters or solar electric energy converters. Devices that directly convert solar into electric energy are generally called photovoltaics [11]. The concept of PV is well-understood and currently thousands of PV based power systems are being deployed worldwide, for providing power to small, remote, grid-independent applications [6]. Additionally, use of solar energy reduces combustion of fossil fuels and the consequent CO2 emmision which is the principal cause of global warming. Global warming is expected to change terrain and climate of many countries unless measures are taken [14–17]. More importantly, in the light of December 1997s Kyoto's protocol on climate change (due to carbon emissions), about 160 nations have reached a first ever agreement (to turn to renewable/wind/PV power) to limit carbon emissions. The capital cost of PV driven power system is about 4000 $/kW and capital cost of conventional power system is about 1000 $/kW [18]. Nonetheless, PV finds application in remote areas (where it is un-economical to extend the utility grid) which lack access to electric grid [18,19]. PV systems have the advantage of minimum maintenance and easy expansion (up-sizing) to meet growing energy needs. PV modularity (modules are available off-the-shelf) is one of its major strength and it allows the users to tailor PV system capacity to the desired situation. PV systems produce electricity during the times when we demand it most, on hot sunny days coinciding with peak electricity consuming periods [10,18].

Despite abundant availability of solar energy, a PV system alone cannot satisfy load on a 24-h basis [18]. Stand-alone diesel gensets are generally expensive to operate and maintain especially at partial loads [20]. Often, the variations of solar energy generation do not match the time distribution of the load. Therefore power generation systems dictate provision of battery storage facility to smoothen the time-distribution-mismatch between the load and solar energy generation and to facilitate for maintenance/outages of the systems [10,21]. PV generated electricity stored in batteries can be retrieved during nights. Use of diesel system with PV-battery reduces battery storage requirement. Research conducted world-wide indicates that hybrid PV/diesel/battery system (represents an economically acceptable compromise between the high capital cost of PV autonomous system and high O&M + fuel cost of fossil fuel generators) is a reliable source of electricity [19]. PV and diesel have complementary characteristics: capital cost of PV is high as compared to diesel, operating cost of PV is low, maintenance requirements of PV are less as compared to diesel, diesel energy is available all the time where as availability of PV is highly dependent on solar radiation [19]. The application of hybrid systems has gained momentum and a number of PV–diesel-battery installations (with capacity factors in the range of 20–35%) exist around the world [19,22,23]. The cumulative installed capacity of all solar systems around the world is about 3120 MWp in 2003. The global installed capacity of solar power is expected to reach 207 GWp by 2020. Also, the projections indicate that by 2020 solar systems can provide energy to over a billion people globally and provide 2.3 million full-time jobs [24]

The research on feasibility of renewable energy in Saudi Arabia has been subject matter of several earlier studies [25–29]. In the present work, the economic analysis of utilization of hybrid PV–diesel-battery power systems to meet the load of a typical residential building (with annual electrical energy demand of 35,120 kWh) in different provinces of K.S.A. has been studied by analyzing long-term (1971–1980) solar radiation data. Five geographically distinct sites covering different provinces/locations of the Kingdom have been selected. The selected locations are Abha (Southern Province), Hofuf (Eastern Province), Qurayat (Northern Province), Taif (Western Province), and Riyadh (Central Province). In general, long-term data indicates that the monthly average daily solar radiation/insolation of K.S.A. varies from 3.03–7.51 kWh/m^2. The prevailing solar radiation intensity has been used as a means to assess the potential of using solar PV technology for residential loads. National Renewable Energy Laboratory's (NREL) or HOMER Energy's HOMER software has been employed to perform the techno-economic analysis. HOMER is a sophisticated tool or computer-model that facilitates design of stand-alone electric power systems [30]. The hybrid systems considered in the analysis comprise of different combinations of PV modules/arrays supplemented by battery storage and diesel gensets. Also, for the above hybrid configuration (for all provinces), the study examines the impact of PV penetration on: carbon emissions (Tons\year), diesel fuel consumption

Table 1
Monthly average daily global solar radiation (w–hr/m^2) of different provinces (major cities) of the Kingdom of Saudi Arabia.

Province [City]	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual avg.
Eastern [Hofuf]	4171	4862	5691	6108	6875	7323	7064	6707	6133	5144	4347	3592	5671
Western [Taif]	4444	5163	5575	5819	5810	6396	6266	5929	5532	5233	4594	4383	5429
Northern [Qurayat]	3464	4736	5486	6421	7095	7418	7514	6936	6077	4741	3804	3027	5562
Southern [Abha]	4372	5275	6083	6025	6527	6459	5746	5985	6197	6433	5923	4853	5824
Central [Riyadh]	3526	4578	5073	5480	5641	6140	6125	5881	5707	5286	4503	3639	5132

***Note*:**
Data represents average of the period 1971–1980
[*Ref.: Saudi Arabian Solar Radiation Atlas*, *Riyadh*, *Saudi Arabia*, *1983*].

(Liters/year), Net Present Cost (NPC, US$), cost of energy (COE, US $/kWh) etc. The investigation also places emphasis on the impact of PV penetration (on diesel fuel consumption, carbon emissions, COE, NPC, excess energy, etc.) for a given hybrid situation for Northern Province (Qurayat).

2. Background information

The Kingdom of Saudi Arabia is basically an arid/desert land with long hot summers, and short cold winters. The topographic features of the Kingdom are characterized by mountains in the west bordering the Red Sea that act as wind deflectors, large desert areas in the interior where high temperatures create low pressure cells, and the Arabian Gulf and Red sea which are sea areas in the east and west, respectively. To the west of K.S.A., the Gulf of Aqaba and the Red Sea form a coastal border of almost 1800 km. The K.S.A. is located within the lattitudes 16°N and 32°N. The month of March marks the beginning of spring and the transition from winter to summer climate. Climatic conditions dictate the availability and magnitude of solar energy at a site. Solar PV systems are characterized by availability of solar insolation/regime/resource. The long-term solar radiation data of different locations used in the present study covers the period 1971–1980 [31]. The information of the locations is furnished in Table 2.

Saudi Arabia has approximately one-fifth of the world's oil reserves, and is the largest oil producer and exporter of total petroleum liquids in the world. Natural gas and oil had 44% and 56% share in conventional power generation in 2008. Fig. 1 shows the contribution of different energy sources in the total conventional power generation in the country [32].

3. Solar radiation data and operational strategy of hybrid system

The long-term (1971–1980) monthly average daily values/profiles of solar radiation of different locations considered in the study are demonstrated in Fig. 2. In general, the monthly average daily values of solar global radiation/insolation (of the locations considered in the study) range from 3.03–7.51 kWh/m^2 [31]. The yearly average daily values of solar radiation of different locations are shown in Table 1. It can be depicted from Fig. 2. that solar radiation is generally higher during the summer months (May to August) as compared to other months (this is due to topography). This implies that solar systems would produce appreciably more energy during summer time. This seasonal pattern/trend of solar radiation matches with the higher load requirements during summer period in Saudi Arabia. This is a favorable characteristic because electricity demand is high during the summer months in K.S.A. Relatively less load can be met/covered during non-summer months because of blocking of sun's rays by clouds.

The long term average data shown in Table 1.has been used for simulations (in HOMER). The energy calculations are made by matching the solar radiation data with the characteristics of PV modules [33]. The characteristics of some of the commercial PV modules are furnished in Table 3. The PV modules which are composed of several solar cells are integrated/clustered in series-parallel arrangement (cells are wired in series to provide greater voltage and in parallel to provide greater current) to form solar

Table 2
Information of selected locations.

Site/Location/Region/Province	Latitude (°N)	Longitude (°E)	Altitude (m)
Hofuf (Eastern Province)	25° 30′	49° 34′	160
Taif (Western Province)	21° 14′	40° 21′	1530
Qurayat (Northern Province)	31° 20′	37° 21′	2
Abha (Southern Province)	18° 13′	42° 29′	2200
Riyadh (Central Province)	24° 34′	46° 43′	564

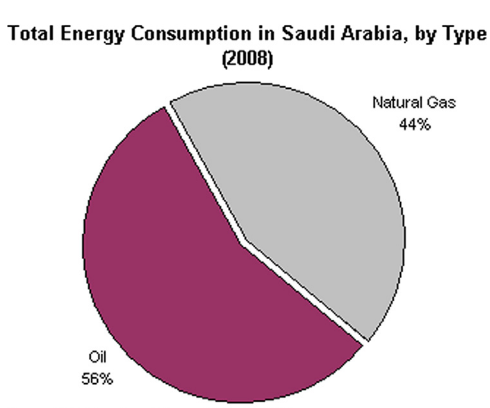

Fig. 1. Conventional power generation sources in Saudi Arabia.

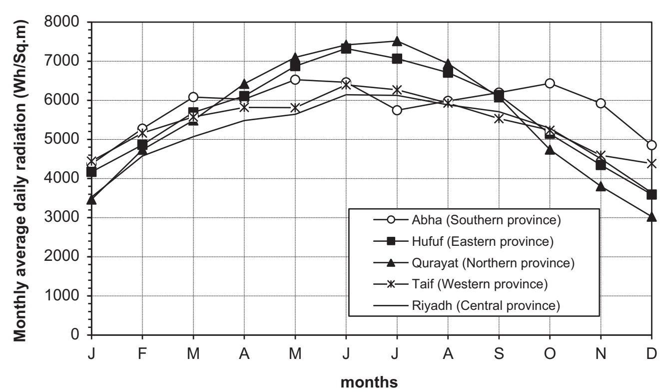

Fig. 2. Monthly average daily solar radiation (long-term average) of different climatic zones (provinces) of Saudi Arabia.

Table 3
Characteristics of some commercial PV modules.

Module, Size, L × W × D	Rated, Power, Rp (W)	Current (A)	Voltage (V)	Module, reference, η
1113 × 502 × 50 (mm)	60	3.5	17.1	0.107
1108 × 660 × 50 (mm)	83	4.85	17.1	0.113
18.5″ × 25.7″ × 2.1″ (in.)	35	2.33	15.0	0.15
25.2″ × 25.7″ × 2.1″ (in.)	50	3.00	16.7	0.15
34.1″ × 25.7″ × 2.2″ (in.)	70	4.14	16.9	0.15
56.1″ × 25.7″ × 2.2″ (in.)	120	7.10	16.9	0.15
50.8″ × 39.0″ × 1.4″ (in.)	167	7.2	23.2	0.15

L: Length; *W*: Width; *D*: Depth
The above modules are High Efficiency Solar Electric Modules and Kyocerasolar Modules.
Power specifications are at standard test conditions of :1000 W/m^2 Solar Irradiance, 25° cell temperature.

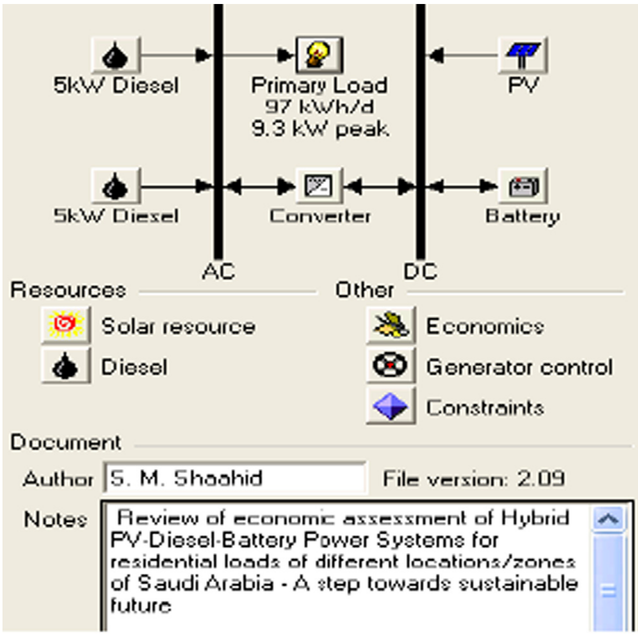

Fig. 3. Schematic of hybrid PV–diesel-battery power system.

arrays. Despite advancements in the state-of-the-art, today's best PV systems can achieve an overall efficiency of about 15–20% [11]. These lower efficiency values may not make this alternative attractive at the moment. However, technological breakthroughs, may change the scenario and pave way for more wide-spread use of PV systems [10,18].

The schematic of hybrid PV–diesel-battery system is shown in Fig. 3. The dispatch strategy is load following type and interaction between different components is as follows: in normal operation, PV feeds the load demand. The excess energy (the energy above the average hourly demand; if any) from the PV is stored in the battery until full capacity of the battery is reached. The main purpose of introducing battery storage is to import/export energy depending upon the situation. In the event, that the output from PV exceeds the load and the battery's state of charge is maximum, then the excess energy is fed to some dump load or goes un-used (due to lack of demand). A diesel system is brought-on-line at times when PV fails to satisfy the load and when the battery storage is depleted (i.e. when the battery's state of charge is minimum).

4. Results and discussions

As a case study and as a representation of residential buildings, the annual average energy consumption of a typical two bed-room house (floor area = 169.8 m^2) has been considered as yearly load (35,120 kWh) in the present study [34]. The daily average load profile is shown in Fig. 4. As illustrated in this Figure, the load seems to peak during June to September. Load influences the power system design markedly. The peak requirements of the load dictate the system size.

In the present work, the sizing of components of hybrid power system has been done using NREL's HOMER (Hybrid Optimization Model for Electric Renewables) software. HOMER is a design software that facilitates design of hybrid electric power systems. HOMER is highly recognized/promising software. NREL has invested thousands of hours in developing this software. This software is highly regarded in renewable energy community. Input information to be provided to HOMER includes: electrical loads data, renewable

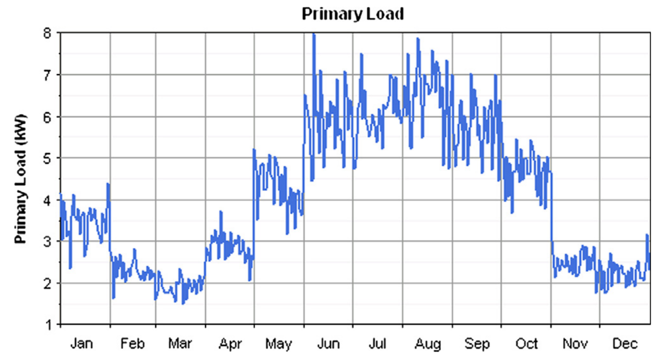

Fig. 4. Daily average load (kW) for a complete year.

resources data, component technical details/costs, constraints, controls, type of dispatch strategy, etc. HOMER designs a optimal power system to serve the desired loads. HOMER is an optimization code, which performs hundreds or thousands of simulations over and over in order to design the optimum system. It uses life cycle cost to rank order these systems [30].

The hybrid systems simulated consist of different combinations of PV panels/modules supplemented with battery bank and diesel generators. The study explores a suitable mix of inter-dependent dominant/key parameters/variables such as PV array power (kWp), battery storage, and diesel capacity to match the pre-defined load (with 0% capacity shortage). As a rule of thumb, diesel generators are sized to meet the peak demand of the power. The peak demand of the present case-study is 9.3 kW as depicted in Fig. 3. In this regard, two diesel generator sets with a combined power of 10 kW (to cover peak load and to cover spinning/operating reserve of about 10% to overcome rapid changes in load) have been considered for carrying out the techno-economic analysis of the hybrid systems. Two diesel gensets (D1, D2) each of 5 kW capacity have been considered. Multiple gensets are used to reduce excess energy. The operating/spinning reserve is surplus electrical generation capacity (over and above that required to cover the load) that is instantly available to serve/cover additional loads. It provides a safety margin that helps ensure reliable electricity supply even if the load were to suddenly increase or the renewable power output were to suddenly decrease.

Several simulations have been made by considering different PV capacities. The PV capacity has been allowed to vary from 0 kW to 24 kWp. The battery storage/bank sizes (kWh) considered include 0 to 6 load-hours/autonomy (equivalent to 0 to six hours of average load, i.e. equivalent to 0 to 6 Surette batteries with details as listed in Table 4). The study assumptions made for making simulations on HOMER are tabulated in Table 4. An earlier study indicates that maximum benefits of battery storage can be realized for a battery capacity of 3 h of autonomy [8]. In this context, battery storage in the present study has been considered as 3 h of average load.

The results of simulations (*for diesel price of 0.1 US$/L*) for different PV penetrations for different locations/zones of Saudi Arabia (for a given battery storage of 3 h; equivalent to 3 h of average load) are presented in Table 5. The details furnished in Table 5. include: PV penetration (%), Net Present Cost (NPC, US$), diesel fuel consumption (Liters/year), carbons emissions that can be avoided (Tons/year), cost of energy generation (COE, $US/kWh) of 1 kWh of energy, etc.

As a starting point (and as a reference), simulations have been performed for PV–diesel systems with zero PV. The COE from diesel system (10 kW Diesel system, no-storage, 0% annual capacity shortage) with 0% PV fraction has been found to be is 0.129 US $/kWh as shown in Table 5. However, for this scenario, the diesel fuel consumption (13,902 l/year) and carbon emissions (10.03 t/year) are on the higher side as compared to the situations with presence of PV and battery storage. It can be noticed from

Table 4
Technical data and study assumptions of PV, diesel units, and batteries.

Description	Data
PV:	
Capital cost	6900 US$/kW
Life time	25 years
Diesel generator units:	
Rated power of diesel unit 1 [D1]	5 kW
Minimum allowed power (min load ratio)	30% of Rated power
No load fuel consumption	0.42 L/h
Full load fuel consumption	1.65 L/h
Rated power of diesel unit 2 [D2]	5 kW
Minimum allowed power (min. load ratio)	30 %of Rated power
No load fuel consumption	0.42 L/h
Full load fuel consumption	1.65 L/h
Batteries:	
Type of batteries	Surette 6CS25P
Nominal voltage (V)	6 V
Nominal capacity	1156 Ah
State of charge (SOC)	40%
Nominal energy capacity of each battery ($V \times Ah/1000$)	6.94 kWh
Dispatch/Operating strategy:	Multiple diesel load following
Spinning reserve:	
Additional online diesel capacity (to shield against increases in the load or decreases in the PV power output)	10% of the load

the results (Table 5.) that in general the PV penetration (renewable energy fraction) has varied from 0 to 69%. In an isolated system, renewable energy contribution of 69% is considered to be high. Such a system might be very difficult to control while maintaining a stable voltage and frequency. The level of renewable energy fraction in hybrid systems (deployed around the world) is generally in the range of 11 to 35% [19]. A trade-off/balance need to be established between different feasible options.

The simulation results indicate (Fig. 5.) that for a hybrid system composed of 4 kWp PV system together with 10 kW diesel system and a battery storage of 3 h of autonomy (equivalent to three hours of average load), the PV penetration is 22%, 21%, 22%, 20%, and 20% (with 0% capacity shortage) at Abha (Southern Province), Hofuf (Eastern Province), Qurayat (Northern Province), Taif (Western Province), and Riyadh (Central Province), respectively. The cost of generating energy (COE, US$/kWh) from the above hybrid system (Fig. 6). has been found to be 0.179 $/kWh, 0.179 $/kWh, 0.178 $/kWh, 0.180 $/kWh, and 0.181 $/kWh (assuming diesel fuel price of 0.1 $/liter) at Abha, Hofuf, Qurayat, Taif, and Riyadh respectively. Literature indicates that COE from PV systems is about 0.20 US$/kWh [35–38].

Also, the simulation results (Table 5.) indicate that for a hybrid system composed of 8 kWp PV system together with 10 kW diesel system and a battery storage of 3 h of autonomy (equivalent to three hours of average load), the PV penetration is 39%., 39%, 40%, 37%, and 36% (with 0% capacity shortage) at Abha (Southern Province), Hofuf (Eastern Province), Qurayat (Northern Province), Taif (Western Province), and Riyadh (Central Province) respectively. The cost of generating energy (COE, US$/kWh) from the above hybrid system has been found to be 0.214 $/kWh, 0.214 $/kWh, 0.214 $/kWh, 0.216 $/kWh, and 0.217 $/kWh (assuming diesel fuel price of 0.1$/liter) at Abha, Hofuf, Qurayat, Taif, and Riyadh respectively. It can be noticed from Table 5, that for a given hybrid system, the PV penetration is higher in Southern Province (Abha) and Northern Province (Qurayat) as compared to other provinces. More importantly, COE for Southern Province (Abha) and) is low as compared to other provinces.

The study has examined the impact of PV penetration (by increasing the PV size) on: carbon emissions, diesel fuel consumption, Net Present Cost (NPC, US$), (COE, US$/kWh) as shown in Table 5. It has been observed that increase in PV penetration results in increase in COE and NPC. On the other hand, increase in PV penetration results in decrease in diesel fuel consumption and carbon emissions. These are welcome features because several countries world-wide are putting significant efforts to reduce diesel fuel consumption and hence to cut-down on carbon emissions. This is a step forward towards sustainable green (carbon-free) future. It can be noticed from Table 5 that the NPC with presence of PV system is high. This highlights that initial cost of PV system in hybrid system is predominant. However, annual operation and maintenance cost of PV/converter system, is 0% of the total O & M+fuel cost.

Furthermore, in view higher PV penetration in Northern Province (for a given scenario) and to facilitate more understanding, attention has been focused on impact of PV penetration on diesel fuel consumption and carbon emissions at Qurayyat (Northern Province) for hybrid system comprising of variable PV+10 kW Diesel+3 h of Battery. It is evident from Fig. 7, that as penetration of PV increases, the fuel consumption of diesel generators decreases which eventually reduce emission of green house gases in the atmosphere.

The percentage fuel savings by using hybrid system (4 kW PV+10 kW diesel system+3 h of Battery, Northern Province) as compared to the diesel only situation is about 19% as shown in Table 5. Moreover, percentage fuel savings increases by increasing the PV capacity. This indicates that introduction of PV panels decreases load on the diesel generators. The diesel fuel savings may only be quantifiable by justifying the additional capital expenditure invested in PV. It has also been observed (Table 5) that the percentage decrease in carbon emissions with 22% PV fraction is about 18% as compared to diesel-only (zero % PV energy) case. The effect of PV penetration (for Northern Province) on diesel fuel consumption, carbon emissions, cost of energy, excess energy generation, etc has been demonstrated explicitly in Figs. 7 and 8. For a given hybrid configuration (for Northern Province), the study exhibits that increase in PV capacity results in decrease in the diesel-fuel-consumption/carbon-emissions and increase in COE./NPC/excess-energy. It should be mentioned over here, that more often, the excess energy produced goes un-used due to lack of demand (sometimes it is fed to dump loads). For a given PV capacity, the lower the excess energy the better is the economy of the PV–diesel-battery systems.

The present study highlights promising or potential provinces of Kingdom of Saudi Arabia for utilizing of solar energy (hybrid PV–diesel power systems). Also, considerable attention is focused by different countries (such as France, Malaysia, Greece, Iran, Bangladesh, Thailand, etc.) world-wide on utilization of hybrid PV–diesel power systems [39–45].

5. Conclusions and recommendations

In view of substantial monthly average daily global solar radiation intensity (3.03–7.51 kWh/m^2), the study indicates that Saudi Arabia is a potential candidate for deployment of solar PV–diesel-battery systems to meet residential loads. The results indicate that for a given hybrid system consisting of 4 kWp PV system together with 10 kW diesel system and a battery storage of 3 h of autonomy (with 0% capacity shortage), the PV penetration is 22%, 21%, 22%, 20%, and 20% at Abha (Southern Province), Hofuf (Eastern Province), Qurayat (Northern Province), Taif (Western Province), and Riyadh (Central Province) respectively. The cost of generating energy (COE, US$/kWh) from the above hybrid system

Table 5
Characteristics of PV–diesel-Battery power systems for a given residential load for **different PV penetrations** (solar PV sizes) at various provinces/regions of K.S.A. (based on diesel fuel price of 0.1 US$/L and battery storage of 3 h of average load).

Province/Region	PV penetration(%)	Net present cost (NPC) ($)	Diesel fuel consumption (Liters/year)	Carbon emissions (Tons/year)	Cost of energy (COE) ($/kWh)
All regions (**0** kWp PV+10 kW diesel)	0	71,397	13,902	10.03	0.129
Province/Region (**4** kWp PV+10 kW diesel)	PV penetration(%)	Net present cost (NPC) ($)	Diesel fuel consumption (Liters/year)	Carbon emissions (Tons/year)	Cost of energy (COE) ($/kWh)
Eastern region (Hofuf)	21	99,290	11,382	8.21	0.179
Western region (Taif)	20	99,569	11,473	8.32	0.180
Northern region (Qurayat)	22	98,885	11,311	8.19	0.178
Southern region (Abha)	22	99,333	11,385	8,22	0.179
Central region (Riyadh)	20	100,362	11,606	8.37	0.181
Province/Region (**8** kWp PV+10 kW diesel)	PV penetration(%)	Net present cost (NPC) ($)	Diesel fuel consumption (Liters/year)	Carbon emissions (Tons/year)	Cost of energy (COE) ($/kWh)
Eastern region (Hofuf)	39	118,757	9767	7.05	0.214
Western region (Taif)	37	119,602	9962	7.19	0.216
Northern region (Qurayat)	40	118,594	9719	7.02	0.214
Southern region (Abha)	39	118,617	9770	7.05	0.214
Central region (Riyadh)	36	120,193	10,081	7.27	0.217
Province/Region (**12** kWp PV+10 kW diesel)	PV penetration(%)	Net present cost (NPC) ($)	Diesel fuel consumption (Liters/year)	Carbon emissions (Tons/year)	Cost of energy (COE) ($/kWh)
Eastern region (Hofuf)	50	143,508	9150	6.60	0.259
Western region (Taif)	49	144,098	9304	6,71	0.260
Northern region (Qurayat)	51	143,453	9127	6.59	0.259
Southern region (Abha)	51	143,404	9151	6.6	0.259
Central region (Riyadh)	47	144,672	9413	6.79	0.261
Province/Region (**16** kWp PV+10 kW diesel)	PV penetration(%)	Net present cost (NPC) ($)	Diesel fuel consumption (Liters/year)	Carbon emissions (Tons/year)	Cost of energy (COE) ($/kWh)
Eastern region (Hofuf)	59	169,551	8815	6.36	0.306
Western region (Taif)	57	170,134	8963	6.47	0.307
Northern region (Qurayat)	59	169,472	8788	6.34	0.306
Southern region (Abha)	59	169.479	8188	6.36	0.306
Central region (Riyadh)	55	170,584	9046	6.53	0.308
Province/Region (**20** kWp PV+10 kW diesel)	PV penetration(%)	Net present cost (NPC) ($)	Diesel fuel consumption (Liters/year)	Carbon emissions (Tons/year)	Cost of energy (COE) ($/kWh)
Eastern region (Hofuf)	64	193,163	9600	6.21	0.354
Western region (Taif)	63	196,728	8742	6.31	0.355
Northern region (Qurayat)	65	196,115	8581	6.19	0.354
Southern region (Abha)	65	196,036	8592	6.20	0.354
Central region (Riyadh)	62	197,125	8815	6.36	0.356
Province/Region (**24** kWp PV+10 kW diesel)	PV penetration(%)	Net present cost (NPC) ($)	Diesel fuel consumption (Liters/year)	Carbon emissions (Tons/year)	Cost of energy (COE) ($/kWh)
Eastern region (Hofuf)	69	223,162	8464	6.11	0.403
Western region (Taif)	67	223,596	8580	6.19	0.403
Northern region (Qurayat)	69	223,117	8450	6.10	0.403
Southern region (Abha)	69	222,990	8445	6.09	0.402
Central region (Riyadh)	66	224,020	8656	6.25	0.404

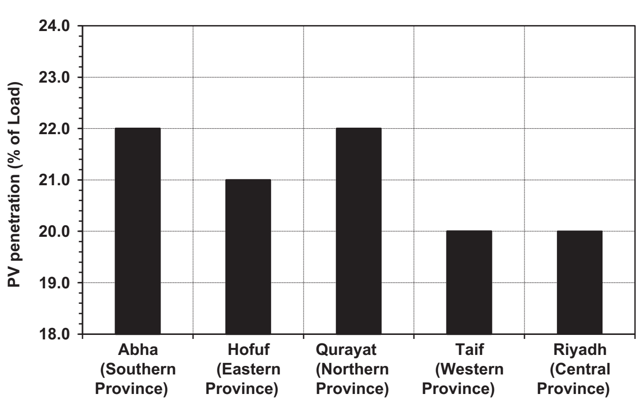

Fig. 5. PV penetration (%) for different selected locations (for hybrid system of 4 kWp PV+ 10 kW Diesel+ 3 h of battery).

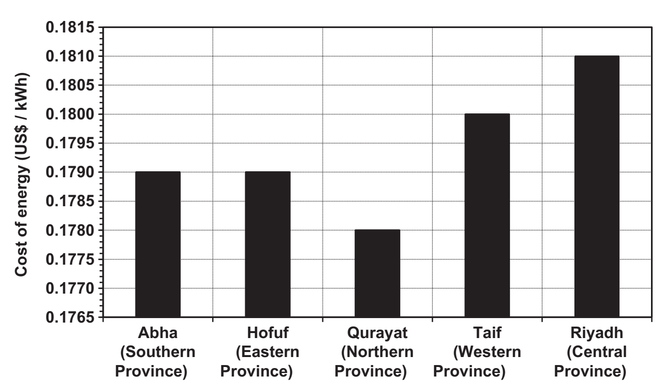

Fig. 6. Cost of Energy (US$/kWh) for different selected locations (for hybrid system of 4 kWp PV+10 kW Diesel+3 hours of Battery).

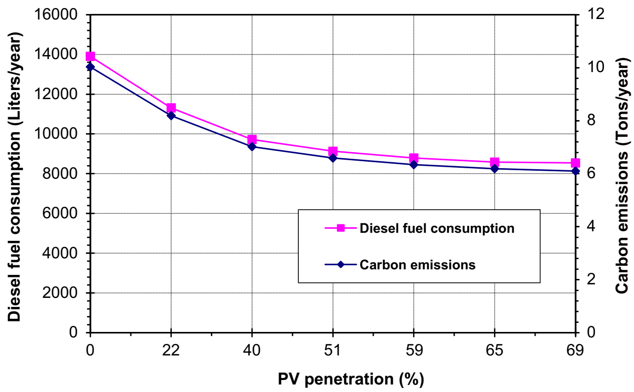

Fig. 7. Impact of PV penetration on diesel fuel consumption and carbon emissions at Qurayat (Northern Province) for hybrid system.

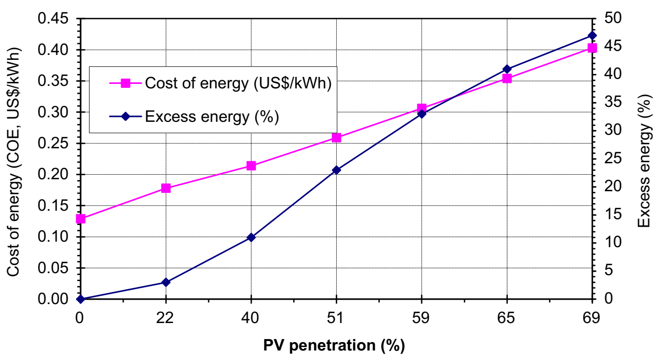

Fig. 8. Impact of PV penetration on COE and excess energy generated at Qurayat (Northern Province) for hybrid system.

has been found to 0.179 $/kWh, 0.179 $/kWh, 0.178 $/kWh, 0.180 $/kWh, and 0.181 $/kWh (assuming diesel fuel price of 0.1$/liter) at Abha, Hofuf, Qurayat, Taif, and Riyadh respectively. For a given hybrid system, the PV penetration is higher in Sourthern Province (Abha) and Northern Province (Qurayat) as compared to other provinces. More importantly, the investigation highlights that COE for Sourthern Province (Abha) and Northern Province (Qurayat) is low as compared to other provinces. Also, the study has examined the impact of PV penetration (of different hybrid configurations of all provinces) on: carbon emissions (Tons/year), diesel fuel consumption (Liters/year), Net Present Cost (NPC, US$), cost of energy (COE, US$/kWh), etc. Furthermore, for a given hybrid configuration (for Northern Province), the study exhibits that increase in PV capacity results in decrease in the diesel-fuel-consumption/carbon-emissions and increase in COE./NPC/excess-energy. The percentage fuel savings by using hybrid system (4 kW PV+10 kW diesel system+3 h of Battery, Northern Province) as compared to the diesel only situation has been found to be about 19%. Also, the percentage decrease in carbon emissions by using hybrid system (4 kW PV+10 kW diesel system+3 h of Battery, Northern Province) as compared to the diesel only situation has been found to be about 18% as compared to diesel-only (zero% PV energy) case.

The present work shows that the potential of solar energy cannot be overlooked. A fraction of Saudi Arabia's energy demand may be harnessed from PV systems. The observations of the present work can be used as a tool for future studies. More importantly, ambitious targets are set world-wide for deployment of renewable energy systems. Many nations are putting great/concerted efforts to contribute to these ambitious targets and eventually to shift to renewable based economy for a sustainable future.

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